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Title: Introduction to neutron dose and dosimetry

Author(s): Mclean, Thomas Donaldson

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Introduction to Neutron Dose and Dosimetry

Presenter: Tom McLean

Los Alamos National Laboratory
RP-SVS Group
Los Alamos, NM

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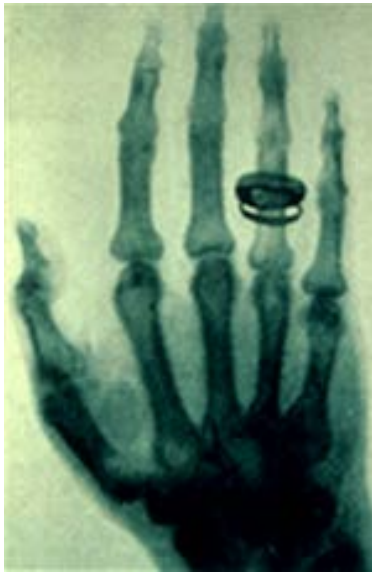
Outline of Presentation

- Introduction
- Radiation effects
  - Acute exposures
  - Deterministic and Stochastic effects
- Operational and protection dosimetric quantities
- Measurement of neutron personnel dose
  - Passive and active dosimeters
- Summary

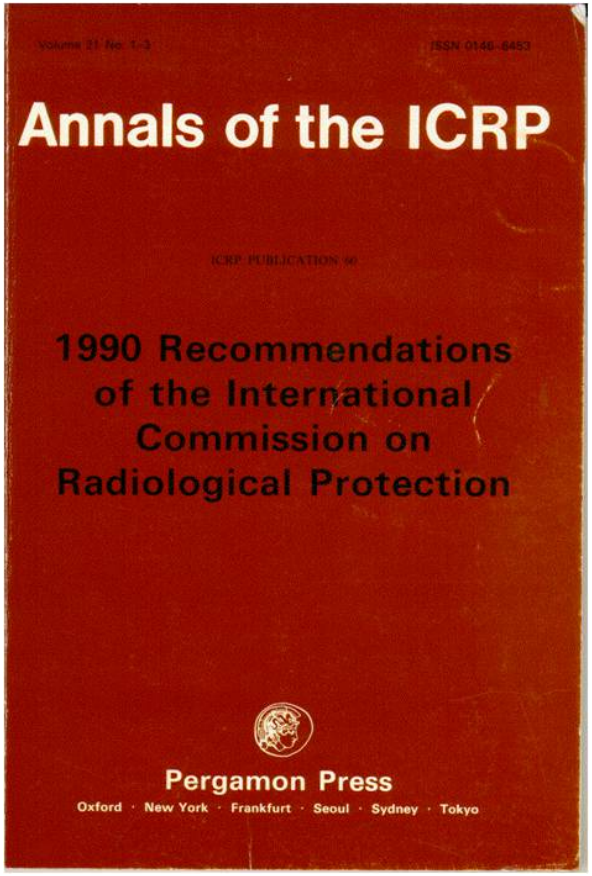
External radiation exposure

- **External Dosimetry** is the field of quantifying the absorbed dose from a source of radiation external to the body. When the source of radiation is removed, no further radiation dose is received.
  - typically performed as an analytical service using a dosimeter (e.g., film badge or thermoluminescent dosimeter (TLD).



Requirements and conventions based on ICRP

- **10 CFR 835 (2007)**
  - ICRP-60/74
- **10 CFR 20**
  - ICRP-26/30
- **EPA**
- **OSHA**
- **States**



Definitions of primary dosimetric quantities

- **Fluence** : Number of particles (photons, neutrons, etc..) incident on sphere of cross-sectional area d*a*. $\Phi = dN/da$ SI units = m^{-2}

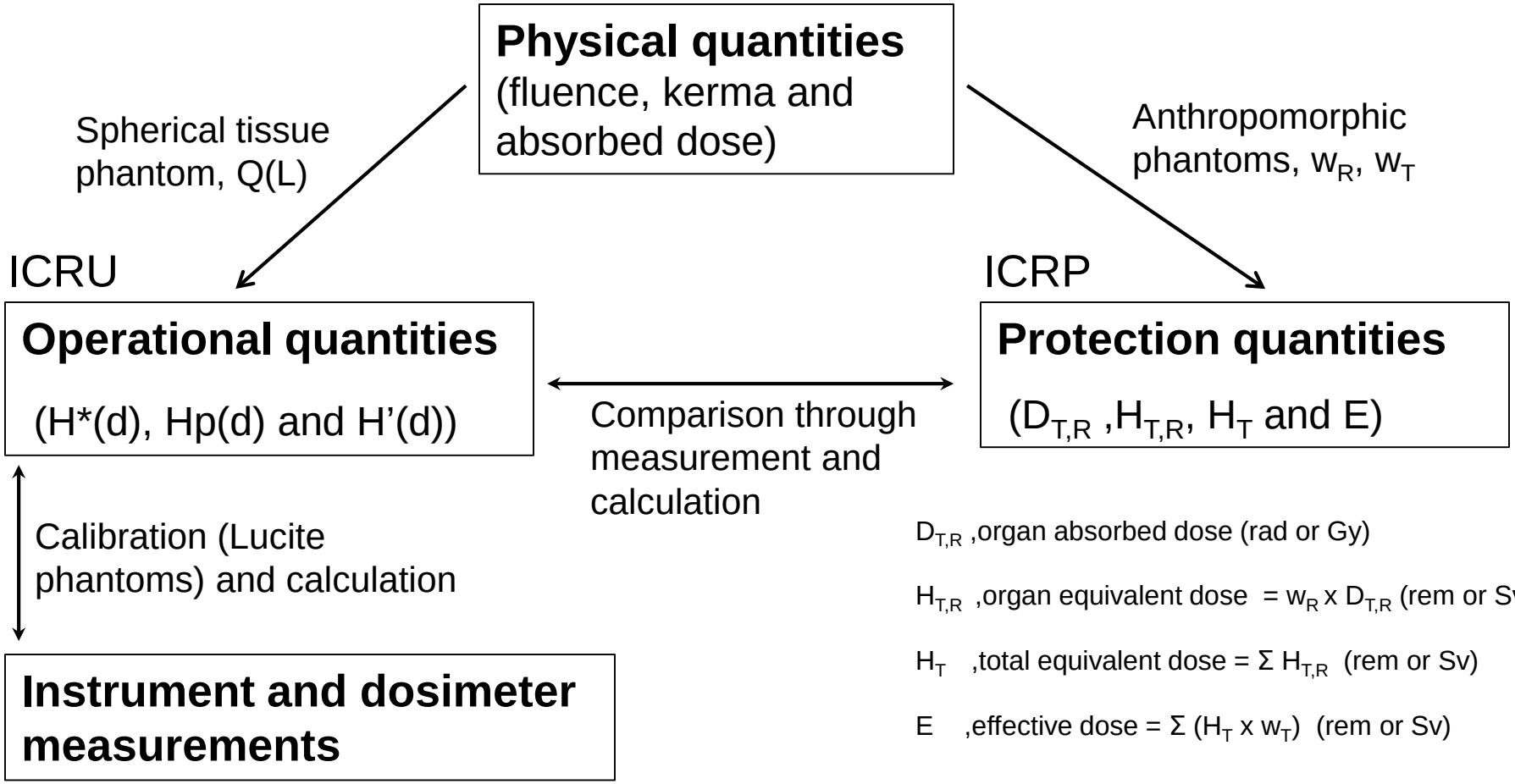
- **Kerma**: Initial sum of kinetic energies of all charged particles liberated by uncharged ionizing particles (e.g. photons and neutrons) in a volume element of mass d*m*. $K = dE/dm$ SI units = J/kg = Gy
  - Kerma approximation assumes kinetic energy deposited locally

- **Absorbed dose:** Average energy imparted by ionizing radiation to matter of mass dm. $D = dE/dm$ SI units = J/kg = Gy

Radiation dose quantities

- Many attempts to define and quantify dosimetric quantities for radiation protection purposes
  - 1920's X-ray exposures prompted first radiation protection standards
  - Revised every few years as more information becomes available
    - Old dose quantities retired or revised and others introduced.
  - Current status is a very confusing system divided into two branches – unlike any other branch of toxicology.
    - ICRP – defines protection or limiting quantities. Calculated only i.e. not measurable ! (unless know spectrum and direction)
    - ICRU – defines operational quantities that can be measured and are conservative estimates of the protection quantities

Dose relationships



$D_{T,R}$,organ absorbed dose (rad or Gy)

$H_{T,R}$,organ equivalent dose = w_R x $D_{T,R}$ (rem or Sv)

H_T ,total equivalent dose = Σ $H_{T,R}$ (rem or Sv)

E ,effective dose = Σ (H_T x w_T) (rem or Sv)

Calculation of dose quantities

- Absorbed dose calculations done using various computer codes
  - Most common are Monte Carlo-based (MCNP, FLUKA, PHITS, EGS4,…)
  - Simulate physical processes using statistical means
  - Transport particles through body and tally energy deposited in various tissues and organs

- Phantoms are increasingly more realistic based on CT and MRI images
  - Voxelized phantoms now routinely used
    - Age and gender specific

Calculation of Effective dose (E)

- Calculate $D_{T,R}$, absorbed dose to each organ (T) for each radiation type (R) as function of incident neutron energy (e)

- Calculate $H_{T,R}$, Equivalent dose to organ
  - $H_{T,R} = \Sigma (w_R * D_{T,R})$ where sum is over all radiation types and w_R is the radiation weighting factor

- Calculate H_T , Total Equivalent dose to body
  - $H_T = \Sigma H_{T,R}$ where sum is over all the organs of interest

- Calculate E, Effective dose
  - $E = \Sigma (w_T * H_{T,R})$ where sum is over all the organs of interest and w_T is the tissue weighting factor as based on radiosensitivity of organ

Radiation weighting factors (w_R)

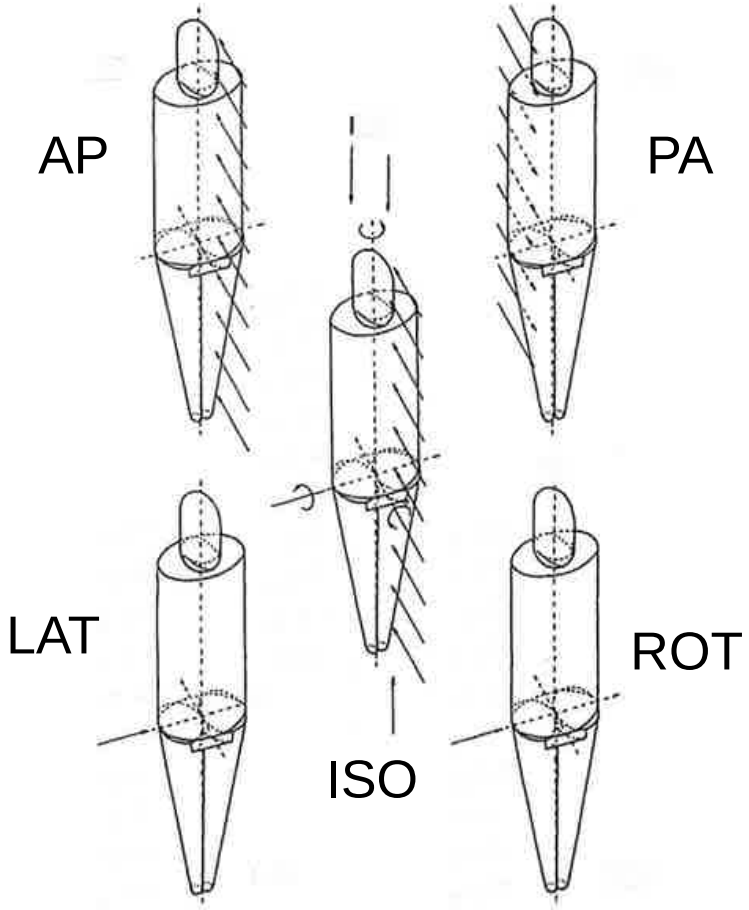
Type and energy of radiation incident on body	ICRP-60
Photons	1
Electrons	1
Neutrons	
< 10 keV	5
10 -100 keV	10
>0.1 - 2 MeV	20
> 2 - 20 MeV	10
> 20 MeV	5
Protons (> 2 MeV)	5
Alpha	20

Tissue weighting factors (w_T)

Tissue /organ	ICRP-26	ICRP-60
Gonads	0.25	0.20
Bone marrow (red)	0.12	0.12
Colon		0.12
Lung	0.12	0.12
Stomach		0.12
Bladder		0.05
Breast	0.15	0.05
Liver		0.05
Esophagus		0.05
Thyroid	0.03	0.05
Skin		0.01
Bone surface	0.03	0.01
Remainder	0.30	0.05

Effective dose: standard irradiation geometries

Effective dose calculated on assumption of uniform whole body irradiation



Effective dose: fluence-to-dose conversion coefficients for each irradiation geometry

- For each irradiation geometry a set of fluence-to-dose conversion coefficients as a function of neutron energy are generated using the approach described earlier.
  - Apply (fold in) these conversion coefficients to the incident neutron fluence to calculate neutron dose
- Conversion coefficients have units of pSv cm^2
- E = neutron fluence (cm^{-2}) * conversion coefficient (pSv cm^2) = pSv
- Repeat for all neutron energies and sum to calculate Effective dose
  - Typically neutron spectrum is binned to form energy groups
  - And a bin-averaged conversion coefficient is applied to each group

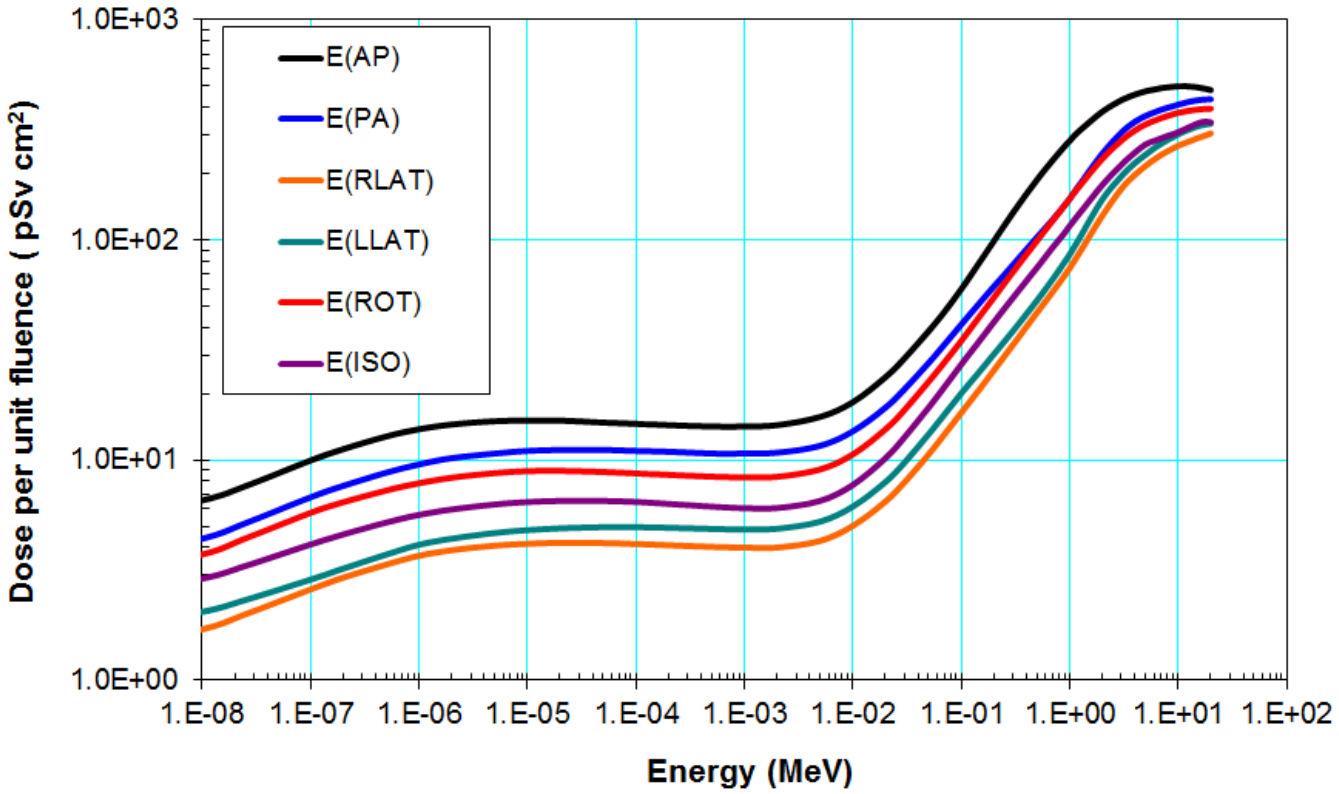
Effective dose: example

- Assume an E(AP) irradiation geometry
- Incident irradiation field consists of two monoenergetic neutrons
  - 1.0 keV and 2.0 MeV

Neutron Energy (MeV)	Fluence (cm^{-2})	Fluence-to-dose factor (pSv cm^2)	Contribution to E (pSv)
0.001	1000.0	14.2	14200
2.0	10.0	282	2820

- E = 14200 + 2820 pSv = 17020 pSv or 1.702 µrem
- If the irradiation lasted for 6 minutes, the average Effective dose rate would be
  - 1.702 µrem / 6 min = 0.284 µrem/min. or 2.84 µrem/h

Effective dose: standard irradiation geometries



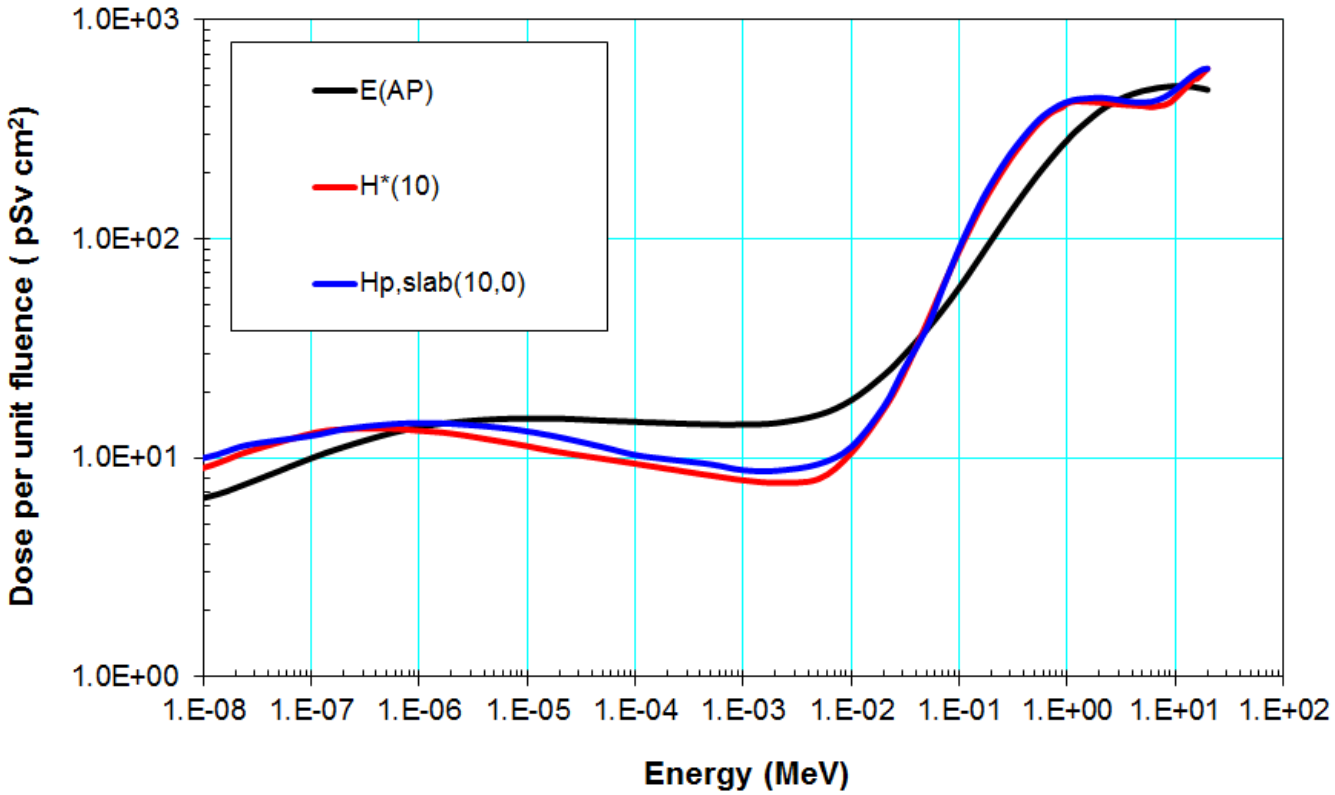
Calculation of operational quantities

- Also based on Monte Carlo modeling
  - Spherical 30cm diameter ICRU tissue phantom (C,H, O, and N)
  - Dose equivalent (rem or Sv) = absorbed dose x Quality factor (analog of w_R)
  - Q is a function of particle type's LET in water

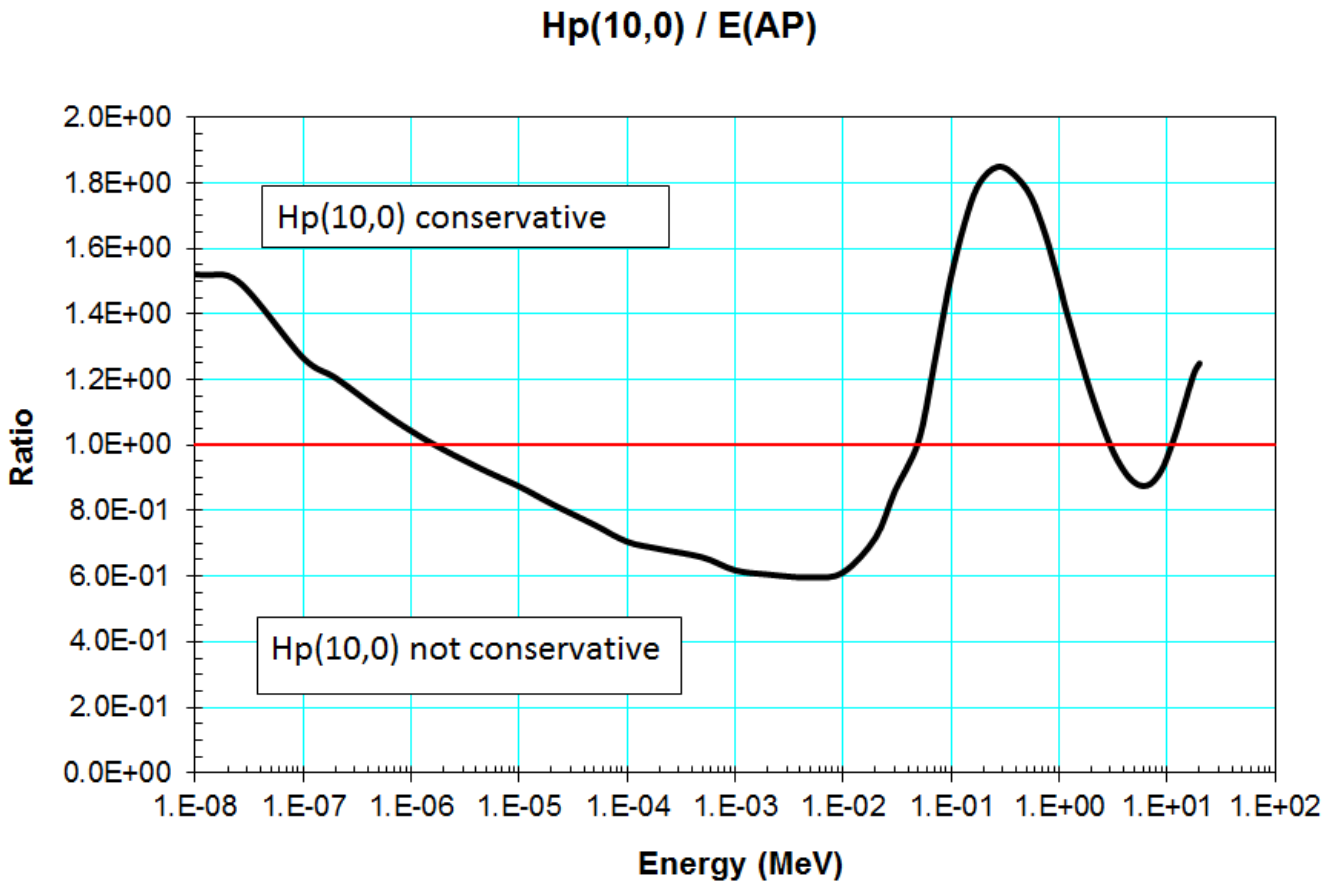
- Personnel monitoring
  - Absorbed dose tallied at specific depths within sphere (0.07, 3 and 10 mm depths)
  - For dosimeter calibration purposes, $H_{p,slab}(d,\alpha)$ also defined for slab tissue phantom ($\alpha = 0^o$-75^o)

- Area monitoring
  - H*(10), ambient dose equivalent
  - $H'(10,\alpha)$, directional dose equivalent ($\alpha = 0^o$-180^o)

Comparison of E(AP) with H*(10) and Hp(10,0) for neutrons



Comparison of Hp(10,0) with E(AP) for neutrons



Breaking news !

- ICRU proposes to retire H*(10) and replace with H* (ambient dose).
  - Similarly, Hp(10) is to be replaced by Hp (personal dose)
- H* is defined with respect to the maximum Effective dose conversion factor as a function of neutron energy.
- Assures conservatism of operational quantity and now E and H* are defined using same calculational approach.
  - E.g. No ICRU phantoms or Quality factors

Acute radiation effects

Syndrome	Dose (Gy)	Dose (rad)	$LD_{50/60}$
Hematopoietic (bone marrow damage)	3 - 5	300 - 500	30 - 60
Gastrointestinal (includes lung damage)	5 - 15	500 - 1500	10 - 20
Central Nervous System (includes cardiovascular damage)	> 15	> 1500	1 - 5

Source: ICRP-60 and assumes low LET radiation, a uniform whole body exposure and a few minute exposure

Deterministic radiation effects

- Formerly known as “non-stochastic” effect.
- Due to relative high doses that cause significant cell death impacting organ function.
- Relatively sharp dose threshold (i.e. predictable).
- Severity increases above threshold dose.
- Example: eye cataracts (Threshold ~ 2-10 Gy for photons).
  - or, 200 – 1000 rad

Stochastic radiation effects

- Due to relatively low doses that impair or modify cell behaviour
  - Affected cells usually do not reproduce (*i.e.* damage is limited).
  - Rarely, leads to delayed effects (*i.e.* cancer) observed later in life (2+ years or more).
  - Modified germinal cells may lead to hereditary disorders.

- No obvious dose threshold
  - Severity of radiation effect not dependent on dose.

- Lifetime fatal probability ~ 4×10^{-2} excess cancer deaths per Sv
  - or, 4×10^{-4} per rem

- ICRP-60 recommends E< 20 mSv (2 rem) per year averaged over a 5 year period for occupational workers
  - General public limit < 1mSv (100 mrem).

Comparison of some radiation doses

Item	Dose (Gy)	Dose (mrad)
Annual dose from sleeping next to someone every night	0.00002	2
Flying NY-LA round trip	0.00005	5
Chest X-ray	0.00010	10
One view abdominal X-ray	0.00060	60
Average annual background radiation dose	0.00360	360
Abdominal CT scan	0.01	1×10^3
NRC Occupational Worker Annual Limit	0.05	5×10^3
Acute dose causing decreased white blood cell count	1	1×10^5
Lethal dose to 50% of exposed individuals in 60 days without medical intervention ($LD_{50/60}$)	4.5	4.5×10^5

Some factors affecting response to radiation

- Personal
  - Gender
  - Age
  - Genetics
  - General health
  - Body type (e.g. BMI)

- Radiation
  - Dose
  - Type and energy of radiation (linear energy transfer rate)
  - Dose rate
  - Area of body irradiated

Neutron dosimeters

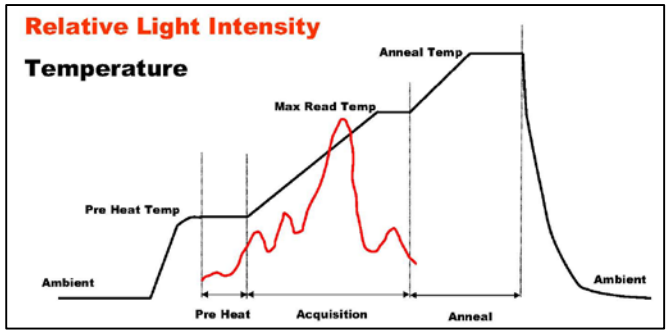
- Intended to give conservative estimate of Effective dose

- Passive neutron dosimeters
  - Require no source of power or signal analysis
  - Examples:
    - Thermoluminescent (TLD) materials
    - Track etch detectors (proton recoil sensitive)
    - Film
    - Bubble detectors

- Active neutron dosimeters (EPDs)
  - Based on thermal neutron detectors (^{3}He, CLYC, ^{6}Li(Eu))
  - And/or, polyethylene converters (i.e. proton recoil) with semiconductor detector

Passive dosimetry: Thermoluminescent dosimeters

- Ionizing radiation raises atoms in thermoluminescent (TLD) material to excited states.
- Some excited atoms unable to return to ground state (trapped).
- Dosimeter is read by applying heat to allow atom to return to ground state which releases photons of visible light.

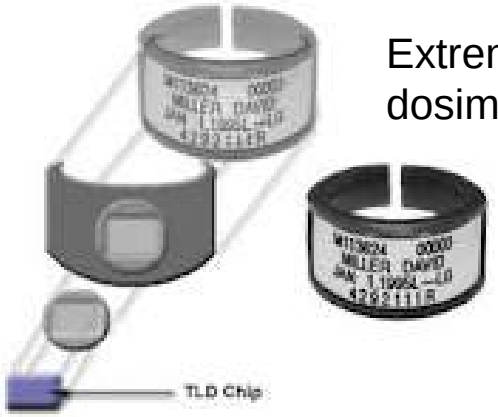


- Total light output is proportional to accumulated dose.
  - Primarily sensitive to thermal neutrons (e.g. based on ^{6}Li-enriched chips)
  - Must subtract gamma contribution (e.g. by using ^{7}Li chips)
- By highest temperature, dosimeter is “zeroed” or annealed and ready for reuse.
  - typical issue periods are 1-3 months.

Thermoluminescent dosimeters (TLD)

LANL model 8823 TLD

Contains chips for beta, photon and neutron dosimetry



Extremity dosimeters

TLD reader

TLD-based dosimeters: Advantages and Disadvantages

Advantages

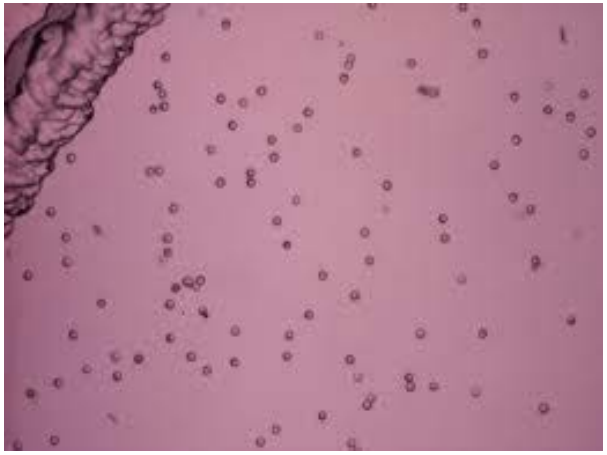
- Relatively Tissue Equivalent for photons
- Useful over long issue periods
- Re-usable
- Relatively inexpensive
- Good systematic QA possible
- Very good lower limit of detection (<10 mrem)
- Wide dose range (> 500 rad)

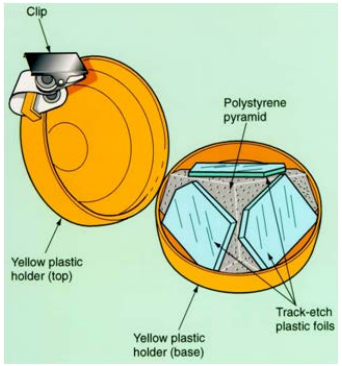
Disadvantages

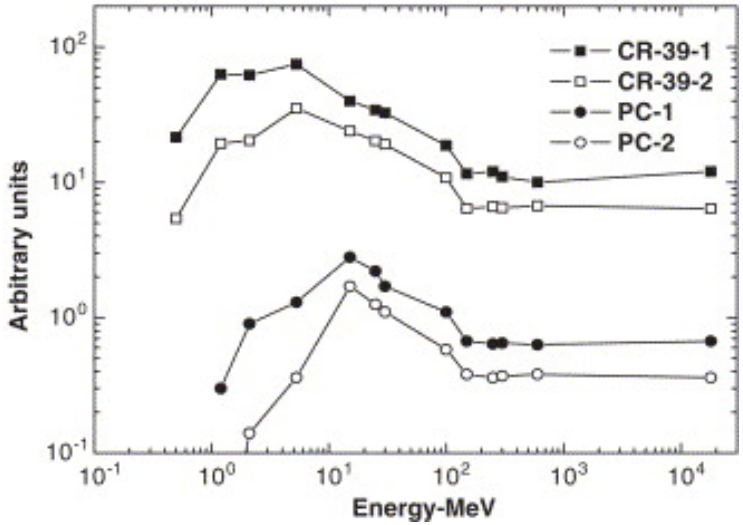
- Not tissue-equivalent for neutrons
- Spatially dependent response
- Light sensitive
- Fading
- Temperature sensitive
- Sensitive to grime (non-radiation induced signal)

Passive dosimetry (neutrons)

- Track etch detectors
  - Proton recoil leaves track in foil
  - Chemical etching magnifies for visual counting
  - Number of tracks proportional to dose
  - Excellent energy response but labor intensive
  - Expensive as foils not reusable



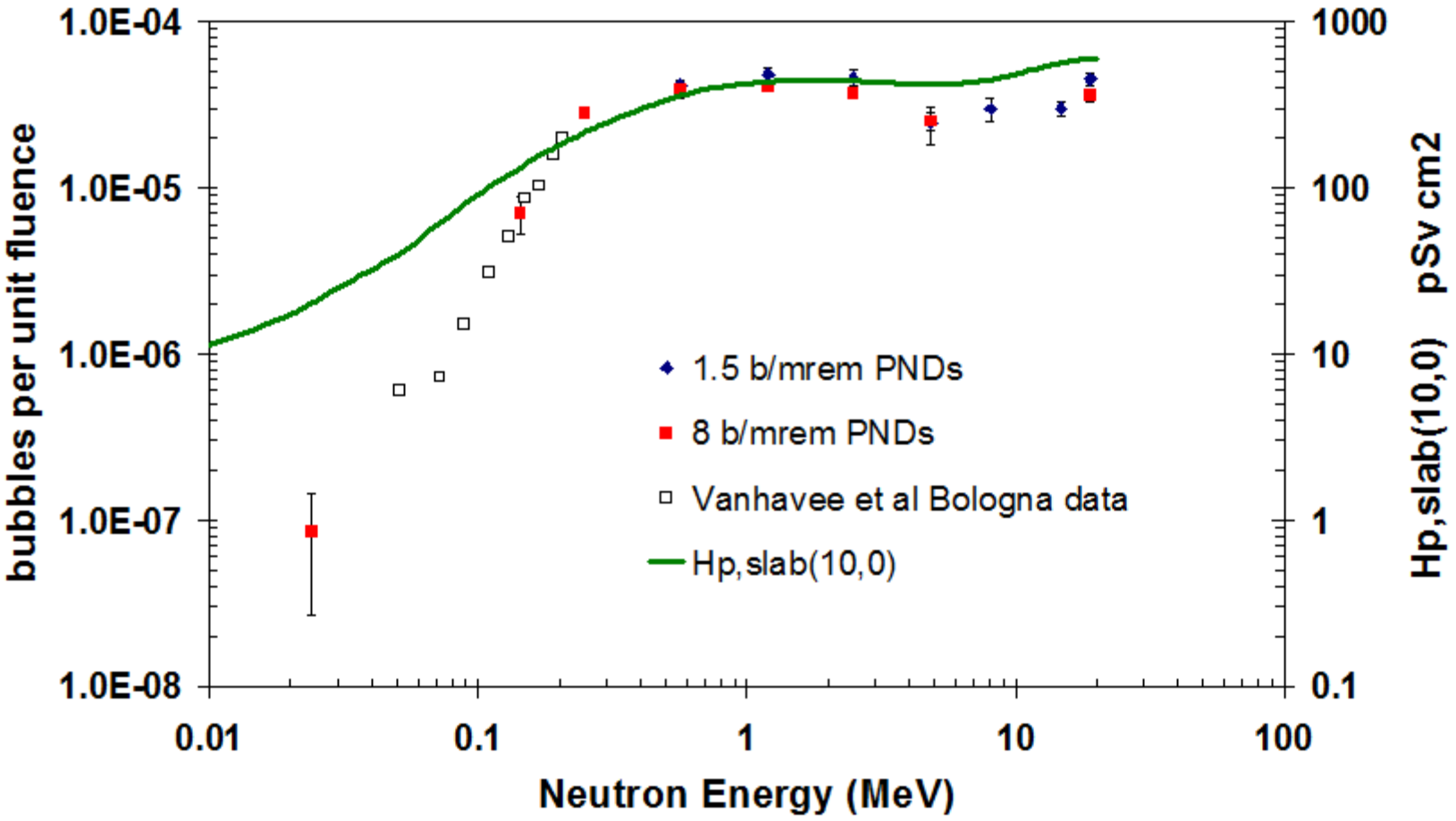




Passive dosimetry: Bubble dosimeters

- Superheated liquid droplets (i.e. in liquid state well above normal boiling point) contained in gelatinous matrix.
  - Droplets ~ 50 µm in diameter
- Droplets can nucleate (boil) if minimum amount of energy deposited within dependent upon:
  - Droplet superheat (function of temperature and pressure)
- Dosimeter bubble counts read by eye or with readers (camera or acoustically based)
- Intrinsic tissue equivalent response
- Number of bubbles proportional to dose
- Can be annealed by applying external pressure
- Gamma insensitive

Average bubbles per unit fluence normalized to a sensitivity of 1 b/mrem



Active dosimetry

- Electronic personnel dosimeters (EPDs)
  - Neutron and/or photon and beta models available
    - ^{3}He, CLYC, ^{6}Li detectors for neutrons
  - Real-time indication of Hp(10,0) dose and dose rate
  - Stores dose history
  - Alarms at preset dose (rate) limit
  - Not yet approved as dose-of-record at LANL
  - Expensive
  - Can be shock and RF sensitive
  - Some models include bluetooth and GPS capability

Examples of EPDs

Summary

- Current state of dosimetric quantities is very confusing but some improvements are coming.
- Both Effective dose and the various operational quantities are dependent on; particle type, energy and orientation wrt human body
- Personnel dosimetry accomplished through passive or active devices
  - External and internal QA programs validate dosimetry programs